PROCESSING AND ANALYSIS OF UXO SIGNATURES MEASURED WITH MTADS

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ABSTRACT

The Multisensor Towed Array Detection System (MTADS) has been developed by the Naval Research Laboratory for use at defense sites to detect, locate and classify buried unexploded ordnance (UXO). To assist in this task, algorithms are being developed that will locate and characterize UXO based on measured magnetic and electromagnetic induction signatures. To validate and improve upon these algorithms, an extensive set of controlled measurements have been made over a variety of ordnance ranging from submunitions to 500 lb. bombs.

Analysis of the total field magnetometer measurements made by MTADS indicate that the magnetic signature of ordnance can be completely modeled as a magnetic dipole over a large range of size, depth, and orientation. No higher order magnetic moments were evident. The location and depth of the magnetic dipole accurately reflects the location and depth of the ordnance to within the limitations of the measurement system (±0.05 m). The strength and the direction of the measured dipole moment were found to scale as a function of ordnance size (diameter and length), ordnance orientation relative to the earth's geomagnetic field, and any permanent magnetization of the ordnance. The scaling is such that a measured dipole strength and direction can not be used to uniquely determine a particular ordnance size and orientation. Assuming the ordnance is not strongly magnetized, an effective size can be calculated within 20-30% of the actual ordnance diameter.

Analysis of the pulsed induction sensor measurements made by MTADS indicate that the signatures of ordnance can not be simply modeled as the dipole response of a ferrous sphere to a pulsed transmitter field. The signals are highly dependent on the aspect ratio of the ordnance (length to diameter) and the orientation of the ordnance relative to the transmit coils. The DC response of a prolate spheroid can be used to model these dependencies. A unique measurement of an object's EM signature would require different orientations of the EM sensor's transmit coil.

Based on these observed parameter dependencies of the magnetic and EM signatures of UXO, an improved fitting algorithm could be obtained by combining the data from both sensors. The magnetic signature accurately determines location and depth of the UXO and gives an estimate on the size. Given this information, the EM signature can determine aspect ratio and orientation.

INTRODUCTION

The Naval Research Laboratory has been developing and field testing the Multisensor Towed Array Detection System (MTADS) for the purpose of ordnance detection and site characterization (McDonald et al., 1997). The system consists of a field rugged, low magnetic signature vehicle and towed geophysical sensor arrays. Two sensor arrays have been developed: an array of eight total field magnetometers (Geometrics 822) and an array of three time domain electromagnetic induction sensors (modified Geonics EM61). The sensor data is positioned by a real-time, centimeter level accuracy GPS system and recorded by PC-based data acquisition system.

The data is transferred to a workstation-based Data Analysis System (DAS) which provides a graphical user interface for handling site survey data management, sensor and navigation quality checking and editing, mapping and display of the sensor data, and user-interactive analysis of magnetic and electromagnetic anomalies caused by buried UXO. In the DAS target analysis mode, the operator uses the cursor to select a magnetic or electromagnetic anomaly from a displayed survey map. The DAS then applies a Maximum Likelihood Estimation algorithm to the selected data to determine the best model parameters of location (x, y, and depth) and size to match the measurements.

For the magnetic data, the estimation algorithm fits the data to the model of a magnetic dipole. The actual fit parameters are dipole location, dipole strength, and dipole orientation. The dipole strength is related to the induced moment of a ferrous sphere and from this an effective size is calculated. The effectiveness of this fit algorithm depends on the magnetic signature from ordnance actually being a dipole signal and on the strength of this dipole signal scaling with ordnance diameter.

For the electromagnetic induction data, the algorithm fits the data to the modeled dipole response of a conducting, ferrous sphere in a pulsed electromagnetic field (Grant and West, 1965). The fit algorithm returns the location of the object and a size estimate based on the object being either non-ferrous and conducting or ferrous and conducting. Again, the effectiveness of this fit algorithm depends on the electromagnetic signature of ordnance scaling like the electromagnetic signature of a sphere.

Besides being limited by the applicability of the models to actual ordnance signatures, these fit algorithms may return inaccurate estimates under other circumstances. If the ordnance signatures are poorly resolved by the measurement system or the amplitude of the signal is small compared to the noise, the algorithms may fail to converge or return inaccurate results.

To test and improve these fit algorithms, a comprehensive set of ordnance signatures were measured under controlled circumstances by MTADS (Nelson et al., 1997). These tests were carried out at a prepared site either on the surface, in a one meter hole, or in a seven meter well. Background measurements were taken over the site beforehand. Metallic debris was removed from the area. The ordnance were held at various depths and orientations with carefully constructed test jigs. Care was taken to use ordnance with no permanent magnetization. Some test cases with permanent magnetization were also taken.

MAGNETIC SIGNATURES OF ORDNANCE

The data analyzed here was taken with the MTADS magnetometer array 0.25 m above the ground. The eight sensors were positioned 0.25 m apart resulting in an array 1.75 m wide. For small surface objects, a single pass was taken over the object. For objects up to 1 m deep, three passes were taken: one centered over the object, one to the right overlapping by two sensors, and one to the left overlapping by two sensors. For the deepest objects up to seven passes were taken over and to both sides of the object.

All passes were driven in one direction, roughly from south to north. Each magnetometer has a relative offset that is a function of vehicle heading and velocity due to some small magnetic signature of the vehicle and eddy currents on the sensor platform. The offsets are on the order of 5 nT and an attempt has been made to correct for them. Because of nearby buried utilities and a construction site, a variation of over 30 nT was measured across the site. The background runs were averaged together and subtracted from runs with ordnance. After this data cleanup, the RMS noise levels across the site were on the order of 1-2 nT. Measured ordnance signatures ranged from 10 to 600 nT in peak amplitude.

Table 1. Magnetometer Test Matrix

Object	Depth	Azimuth	Inclination
20mm Projectile	Surface	N,E	Horizontal
30 mm Projectile	Surface	N,E	Horizontal
M46 Submunition	Surface	N,E	Horizontal
60 mm Mortar	0.25, 0.5 m	N,NE,E, SE,S	Horizontal 45° Vertical
81 mm Mortar	0.5 m	N,NE,E, SE,S	Horizontal 45° Vertical
105 mm Projectile	0.5, 0.75, 1.0, 1.3 m	N,NE,E, SE,S	Horizontal 45° Vertical
5” Rocket	1.0, 1.2, 1.7, 2.2 m	N,NE,E, SE,S	Horizontal 45° Vertical
250 lb. Bomb	2.0, 3.77 m	N, E, S	Horizontal
500 lb. Bomb	1.85, 4.23 m	N, E	45°

Table 1 lists the depths and orientations of each measured ordnance item. The MTADS fit algorithm found reasonable dipole fits in all cases. Figure 1 compares the measured magnetic signature from a 105 mm projectile 0.5 m deep (black contours) with the

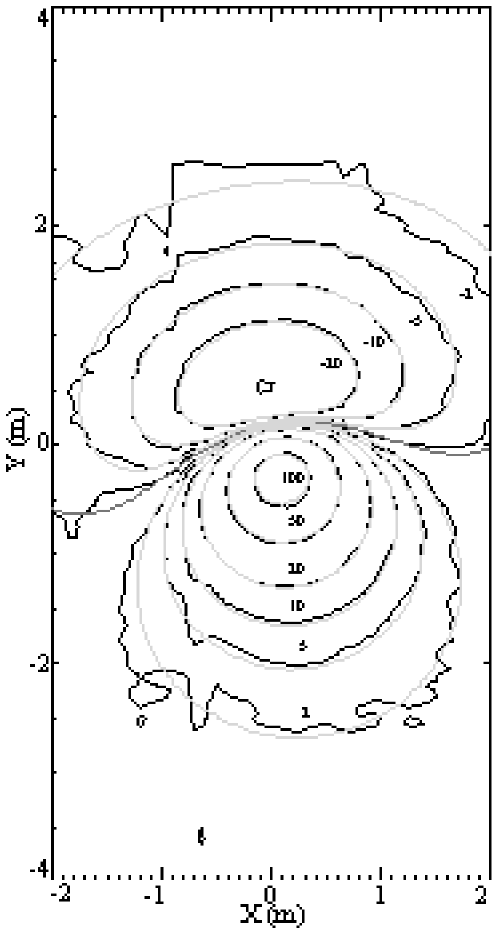

Figure 1. Contours of measured (black) and modeled (gray) magnetic signal from horizontal 105 mm projectile 0.5 m deep.

modeled dipole fit (gray contours). The fit algorithm placed the dipole within 0.06 m of the ordnance's (x, y) location and within 0.02 m of the 105 mm's depth. Currently, the fit algorithm returns a "goodness of fit" parameter based on the square of the spatial coherence between the measured magnetic signal and the modeled dipole fit. This parameter ranges from 0 to 1 where 1 is a perfect match. The 105 mm case above resulted in a match of 0.9944.

Overall the "goodness of fit" parameter ranged from 0.8212 to 0.9964. In cases where it fell below 0.97, the average error in the fit location and depth began to increase. These cases were found to fall into three categories: shallow ordnance where the spatial extent of the magnetic signal was on the order of the sensor spacing, ordnance with low signal to noise ratios (SNR), and deep objects where the signal extended outside of the measured area. For well measured, strong SNR cases (>20 nT), the "goodness of fit" parameter ranged from

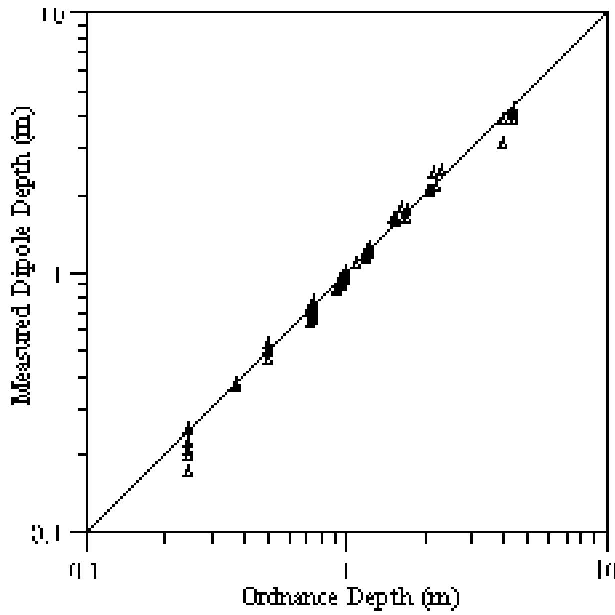

Figure 2. Measured dipole depth versus actual depth of ordnance.

0.9691 to 0.9964 with an average value of 0.9876. These signals are well described by a magnetic dipole signal. Subtraction of the modeled dipole signal from the measured data found no coherent residual signal that would indicate higher order magnetic moments in the magnetic signature.

The standard deviation in the (Δx, Δy) location errors were 0.05 m for the well measured, high SNR objects. This is on the order of the accuracy of the GPS system used. For the low SNR (10-20 nT) objects, these errors increased to 0.10 m. The shallow ordnance had larger errors in Δx (0.08 m) than in Δy (0.04 m). All of the data was collected with the vehicle driving in the y direction; so, the sensor sampling was effectively 0.25 m in the x direction (array spacing) and 0.05 m in the y direction (sampling rate times the vehicle speed). The deep ordnance had the largest standard deviation in the location errors, on the order of 0.40 m. The spatial extent of these signals extended outside of the measured area and this may be the cause of these errors.

Figure 2 plots the depth estimate of the dipole versus the actual depth of the ordnance. The depth plotted here is actually the distance below the sensor array (the sensor array was 0.25 m above the ground). The dipole fitting algorithm gives very accurate depth estimates. The standard deviation in the relative depth errors (ΔZ / Z) is 0.06. The largest relative depth errors are about 0.18 and occur for both the shallow and deep cases.

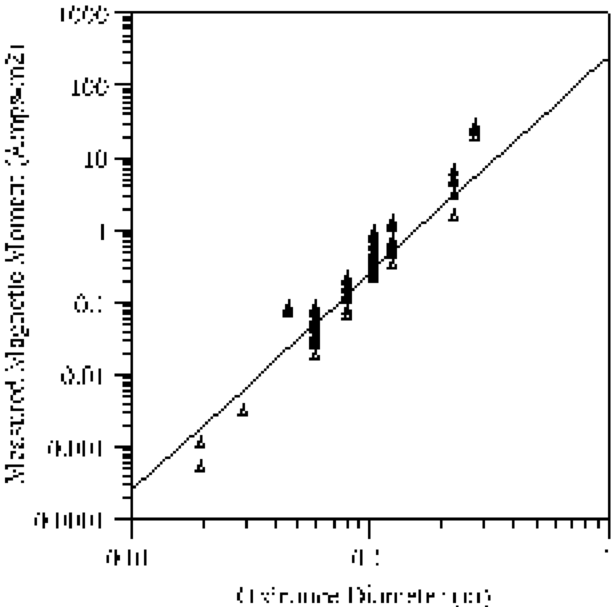

Figure 3. Measured dipole moment versus actual ordnance diameter.

The strength of the dipole moment is plotted versus ordnance diameter in figure 3. The line shows the predicted dipole moment based on equating the volume of the ordnance to the volume of a sphere and calculating the induced dipole moment for this equivalent sphere. Currently, the MTADS fitting algorithm estimates size based on this equivalent sphere. The measured dipole moments show significant variation for a given object. As the 105 mm at 0.5 m depth is varied through 11 orientations, its moment varies from 0.2543 to 1.018 Amps-m^2. Table 2 presents the variation in moments for the 60 mm mortar, the 81 mm mortar, the 105 mm projectile, and the 5" rocket over various ranges of orientation and depth. The result this has on the effective size calculated is shown for each. For the 105 mm, the range in effective sizes goes from 0.100 to 0.163 m. Using this effective size estimate, it is not possible to resolve between ordnance items of similar size.

Table 2. Ordnance Moments and Effective Sizes

Object	Average Moment (Amps-m^2)	Range of Moments	Average Size (m)	Range of Sizes
60 mm	0.0583	0.0235 - 0.104	0.06	0.045 - 0.074
81 mm	0.1583	0.0767-0.259	0.084	0.067-0.101
105mm	0.6098	0.254-1.10	0.132	0.100-0.163
5" (127mm)	0.9572	0.415-1.63	0.153	0.118-0.186

Both the strength and the direction of the dipole moment changes as the orientation of the ordnance is changed.

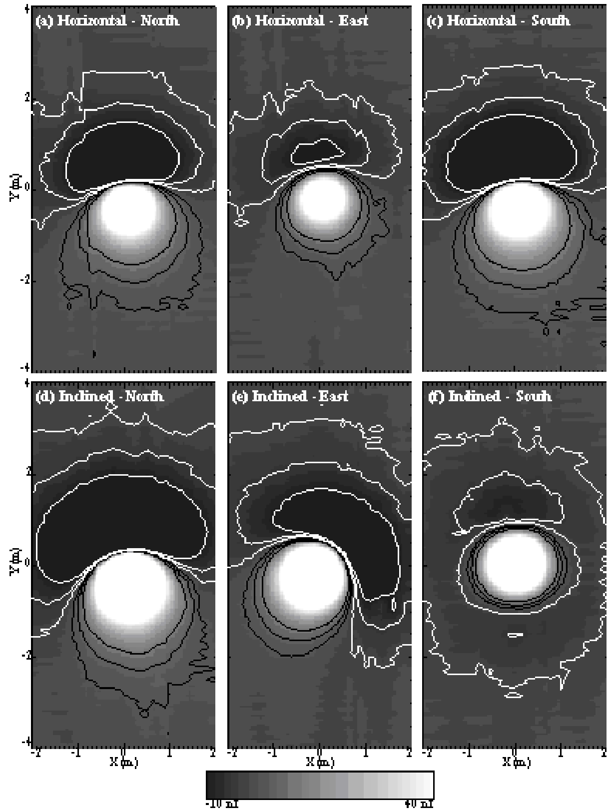

Figure 4. Images and contours of magnetic data from 105 mm projectile 0.5 m below the surface in 6 different orientations. Contour levels are -10, -5, -2 (white) and 2, 5, 10 (black).

Figure 4 shows the magnetic data for the 105 mm at 0.5 m depth at six different orientations. Figures 4 (a)-(c) plot the 105 mm horizontal pointing magnetic north, east, and south (magnetic north is 100 degrees counter-clockwise from the x axis). Figures 4 (d)-(f) show the 105 mm inclined 45 degrees nose down from the horizontal, again pointing north, east, and south. In the horizontal case, all three magnetic dipoles are oriented towards magnetic north, but when the ordnance is aligned with east, the dipole strength is significantly weaker. In the inclined case, the dipole moment points first north, then east, then almost vertically up as the ordnance goes from north to east to south.

To model the complex behavior of the dipole moment as a function of ordnance orientation, a prolate spheroidal model has been suggested (Altshuler, 1996). The induced dipole moment from this model is a function of the length of the major and minor axes of the spheroid and the orientation of the spheroid relative to the earth's magnetic field. In Figure 5, (a) the magnitude of the dipole moment, (b) the azimuth angle of the moment, and (c) the inclination angle of the moment are plotted as

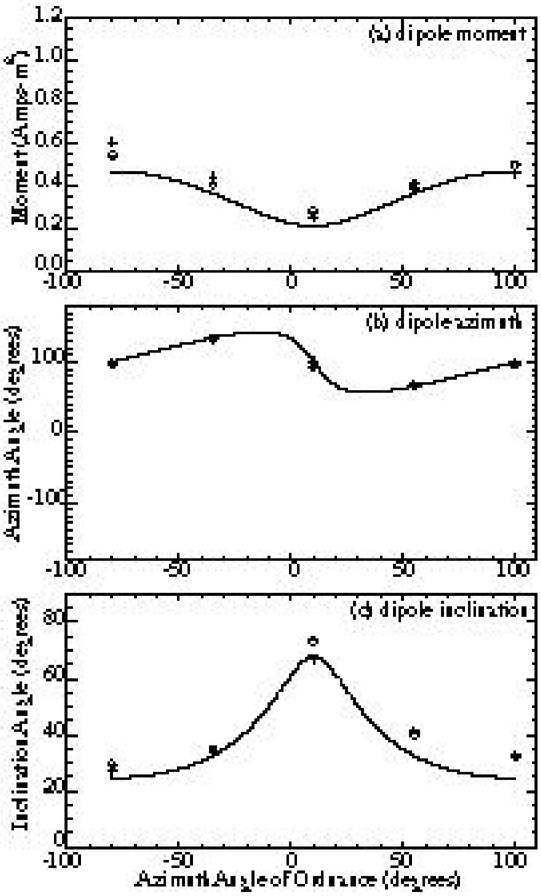

Figure 5. Dipole moment parameters of (a) magnitude, (b) azimuth, and (c) inclination as a function of the azimuth angle of a horizontal 105 mm projectile.

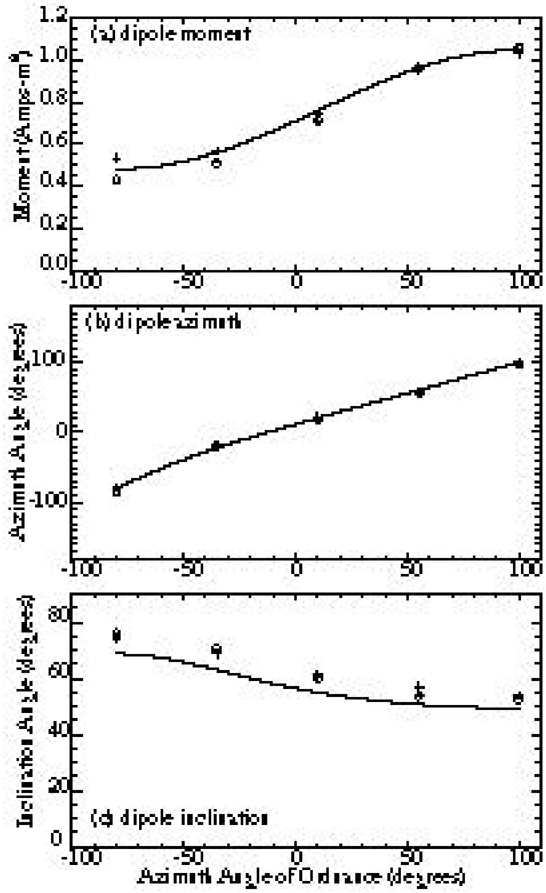

Figure 6. Dipole moment parameters of (a) magnitude, (b) azimuth, and (c) inclination as a function of the azimuth angle of a 45° inclined 105 mm projectile.

a function of the azimuthal direction of the horizontal 105 mm projectile at the depths of 0.5 m (plus symbols) and 0.98 m (diamonds). The azimuth angle used here is defined counter-clockwise from the x axis. The inclination angle is defined positive pointed down from the horizontal x-y plane. Magnetic north has an azimuth angle of 100 degrees and an inclination of 68 degrees at the test site. The curves in each figure indicate the predicted moments for a prolate spheroid 0.105 m in diameter and 0.3885 m in length. There is reasonable agreement with the measured dipole moments. It should be noted that the 105 mm is flattened on one end and pointed on the other. It is interesting to note that when the ordnance is pointing to the north its dipole moment is weaker than when it is pointing to the south. For the symmetric spheroid, both orientations produce the same moment. Besides the effect of shape, another possible explanation for this could be a small permanent magnetization along the axis of the ordnance. Figure 6 plots the same dipole parameters as a function of ordnance azimuthal orientation for the 105 mm inclined 45 degrees. The two depths are at 0.5 m (plus) and 0.7 m (diamonds). Again, there is reasonable agreement with the prolate model.

From the magnetic signatures of ordnance used in this test set, it is only possible to measure a dipole signal and determine the parameters of this dipole. While the location and depth of this dipole can be used to accurately determine the ordnance location, the strength and orientation of the dipole can not be used to uniquely determine the diameter, length, and orientation of the ordnance. At best an effective size can be estimated that has a range of overlap with similar sized ordnance. If the ordnance has a strong permanent magnetization, the situation is harder to resolve in that the measured dipole moment will be the vector sum of the permanent and induced moments.

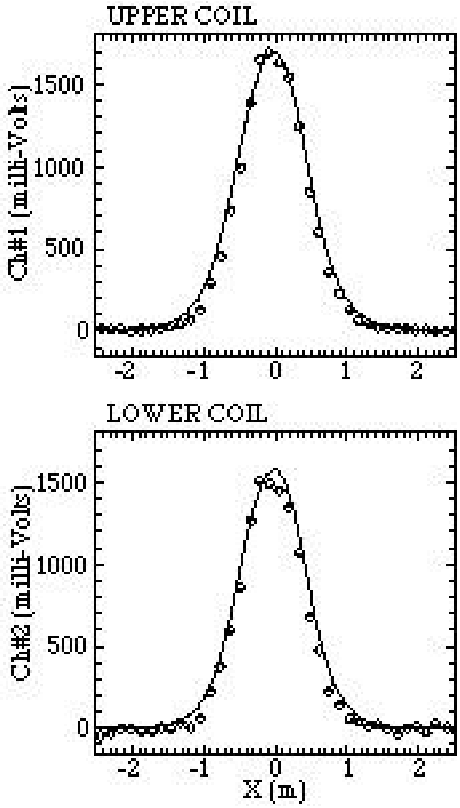

Figure 7. Measurement (symbols) and model (curve) of EM signal from ferrous sphere 0.25 m below surface.

INDUCED EM SIGNATURES OF ORDNANCE

The MTADS EM array consists of three half overlapping modified Geonics EM61 sensors. The coils are 1 m square and the array swath width is 1.5 m. Each sensor has a lower receiver co-located with the transmit coil and an upper receiver 0.4 m above this. The lower coil is 0.4 m above the ground. The data is sampled at 10 Hz and the vehicle was driven at 1.5 m/s, resulting in an along track (Δy) sampling of 0.15 m. Like the magnetometer array, a single pass was driven over surface objects and three passes centered about the object were driven for deeper objects. The cross track sampling (Δx) is equal to the coil spacing (0.5m). Each receiver coil had a different bias offset which had to be corrected. Over long time scales (> 1 minute), these bias levels would drift. Background runs were taken prior to collecting data and used to clean up the site of small metallic debris. Because the EM sensors are relatively insensitive to objects more than several meters off to the side, no subtraction of background data was necessary. RMS noise levels are on the order of 15 mV for the lower receivers and 3 mV for the upper receivers. The upper receiver has a larger effective gain and produces a peak signal equal to the lower coil for an object on the surface. The larger noise level for the lower coils is thought to be due to their proximity to the transmit coils. Signal levels for the various test ordnance varied from 10's to 1000's of millivolts.

Figure 7 plots the measured signal from the center EM sensor as it passes over a spherical 16 lb. ferrous shotput that is 0.25 m below the surface. The symbols represent measured data points and the curve is the model result from the fit algorithm. The model predicts the correct signal shape, signal amplitude, and relative amplitude between the upper and lower coils.

While the EM fit algorithm based on the sphere model was found to be effective for obviously round objects, it was found not to be able to predict the measured signal shape or amplitude of elongated ordnance. At any given depth, the measured ordnance signal was found to vary

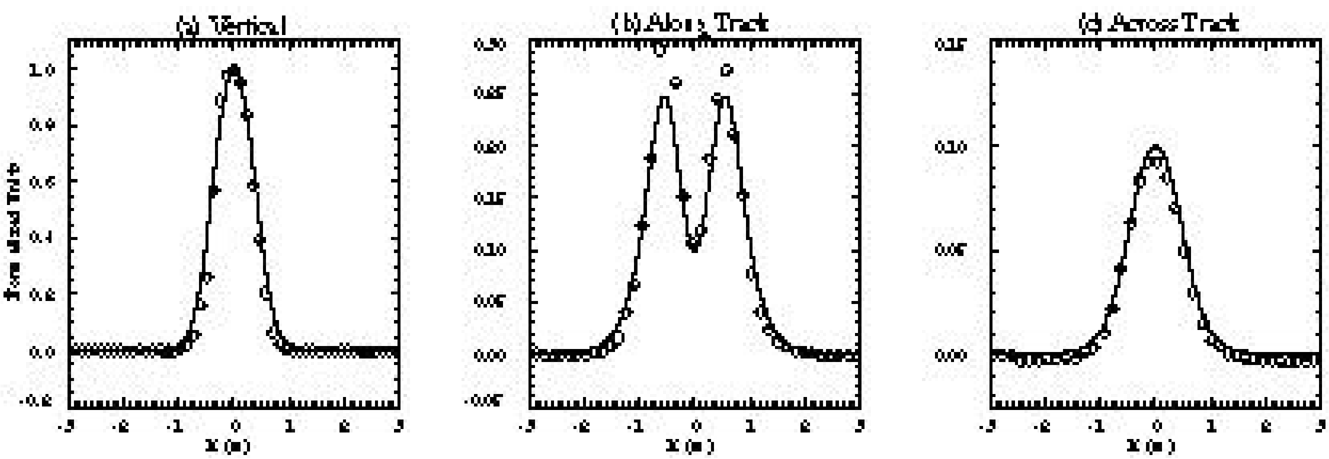

Figure 8. Measured (symbols) and modeled (curves) EM signals from upper, center EM coil of MTADS array driven over a 2.75" rocket. The rocket is oriented (a) vertically, (b) horizontal along the direction of travel, and (c) horizontal perpendicular to the direction of travel.

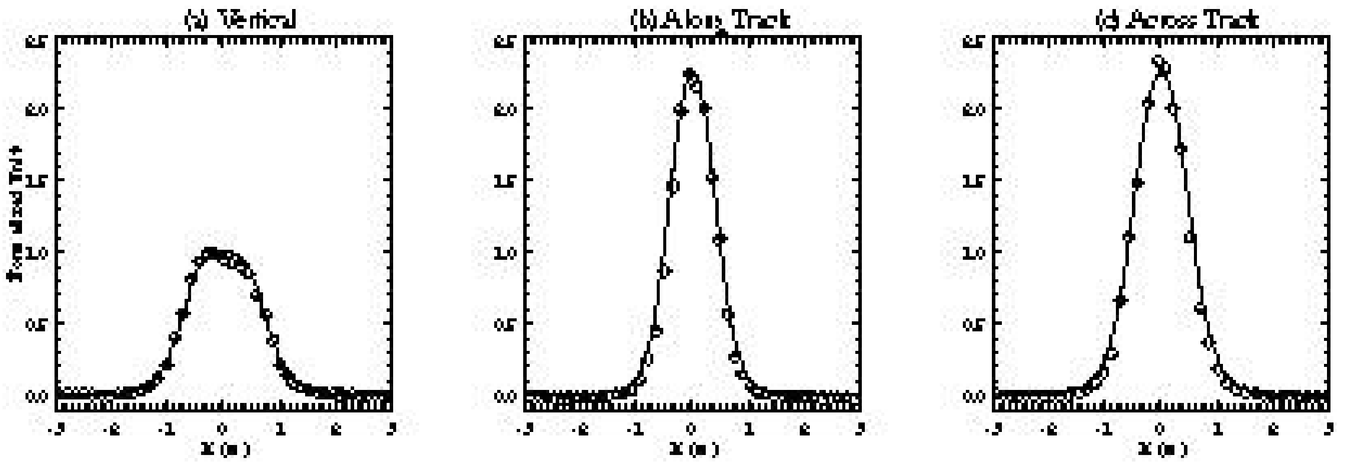

Figure 9. Measured (symbols) and modeled (curves) EM signals from upper, center EM coil of MTADS array driven over a 10 lb. ferrous disk. The disk is oriented (a) vertically, (b) horizontal along the direction of travel, and (c) horizontal perpendicular to the direction of travel.

significantly from the sphere model as a function of the ordnance orientation relative to the direction of travel of the EM array. Figure 8 plots the measured signal from a 2.75” rocket that is 0.25 m below the surface as it is oriented (a) vertically, (b) horizontally along the direction of travel, and (c) horizontally across the direction of travel (diamonds represent measured data points). The sphere model does not account for object orientation and would return the signal shape shown in figure 7 for the shotput. The spherical shotput has an effective volume similar to the rocket and the sphere model would predict a comparable amplitude. The rocket had a peak signal of 7000 mV for the vertical case. The amplitudes plotted in figure 8 are relative to this peak amplitude. The vertical case has a signal that is narrower than the sphere model and larger in amplitude. The along track case has a signal that is different in shape and amplitude. The cross track case has a signal similar in width to the sphere model.

In an attempt to model the measured sensor response, a prolate spheroid model based on the induced dipole moment for the magnetostatic case was implemented (Das et al., 1990). Because this model does not account for the time response of the object to the pulsed EM transmitter, it can only be used to predict the relative amplitudes of the sensor response. The curves in figure 8 are based on this model and normalized to the vertically oriented case. A diameter of 2.75” and length of 16.5” was used for the model (compared to an actual length of 13”).

In figure 9, similar results are shown for a 10 lb. ferrous disk. In this case, the model is for an oblate spheroid. The interesting thing to note is that the relative amplitude is smaller and the signal shape is broader for the vertically oriented case. This is the reverse of the previous result. The important parameters here are the orientation of the object relative to the transmitted field and the aspect ratio of the object (length over diameter). When an elongated object (aspect ratio > 1) is oriented along the transmitted field, it has a stronger induced dipole moment than when it is oriented perpendicular to the field. For a flat object (aspect ratio < 1), the opposite is true.

Based on these results, it is thought that with some modification, the MTADS sensor arrays can be used to characterize an unknown object’s location, depth, diameter, aspect ratio, and orientation. A comparison of figures 8(a) to 9(a) and 8(b) to 9(b) shows that given an object’s depth and orientation, its aspect ratio can be determined. At a given depth, a vertically oriented object has a broader, rounded signal for small aspect ratios and a narrowly peaked signal for large aspect ratios. At a given depth, a horizontal object along track has a single peak for small aspect ratios and a double peak for large aspect ratios. The cross track case (8(c) and 9(c)) has some differences in signal width, but they are not as obvious. To determine the object orientation, it would be necessary to cross over the object with different transmitter orientations relative to the object in the ground. To uniquely determine both orientation and aspect ratio (given the depth of the object), it would be necessary to orient the EM transmitters in three orthogonal directions relative to the object and measure the signal shape in each case. This can be done in two possible ways with the MTADS EM array: the array can be driven over the object in two orthogonal directions and then the sensors can be turned on their sides and the object driven over a third time, or the array can be configured with the three (or more) EM sensors in different orientations. There are tradeoffs in each case. The question of how to determine object depth has already been answered in the first section of the paper. While the magnetometer array can not accurately and uniquely determine object size, aspect ratio and orientation, it can determine both the position and the depth of the object. This suggests that the way to better characterize an unknown object in the ground is through the combined use of the magnetometer and EM sensor arrays.

CONCLUSIONS

Because of its careful data collection, MTADS has been able to accurately measure the actual magnetic and EM signatures of UXO. The data is well sampled along and across track and accurately positioned.

The magnetic signature of UXO over a wide range of sizes and depths can be completely described as a magnetic dipole. The dipole parameters of location, depth, moment strength, and moment orientation (azimuth and inclination angles) are all that can be determined from this signature. The location and depth of the dipole accurately reflect the true position of the ordnance. The moment strength can be used to calculate an effective size, but with a relatively large uncertainty (20-30%), because size is not the only determining factor in the dipole moment strength. The moment strength and direction depend directly on the ordnance's diameter, length, and orientation relative to the geomagnetic field. The measured scaling of these parameters as a function of ordnance orientation shows reasonable agreement with a prolate spheroid model, but the effects of actual ordnance shape and permanent magnetization may be important factors too. The result of this scaling is that for a given dipole strength and dipole direction, a unique ordnance size and orientation can not be found.

The EM signatures of UXO are not so easily modeled. The dipole response of a ferrous sphere to a pulsed EM sensor does not describe the signal shape or amplitude of elongated UXO. The EM signature is highly dependent on the aspect ratio of the ordnance and the orientation of the ordnance relative to the transmit coil. If different orientations of the transmit coil are used, a unique set of EM signatures may be obtained. Given an object's location and depth, the signal shape and relative amplitude can be modeled with the DC response of a prolate spheroid, and the orientation and aspect ratio of the object determined.

Based on these results, an improved fit algorithm for characterizing UXO would be based on both of these sensors. The magnetic data is useful for determining the location and depth of the object. Given this information, the EM sensors are useful for determining orientation and aspect ratio. From these combined results, it will be possible to better characterize buried UXO and discriminate it from other buried items.

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